HYBRID ELECTRIC VEHICLES

UNIT-2

Architectures of HEVs :

6.2 Architectures of Hybrid Electric Drivetrains

The architecture of a hybrid vehicle is loosely defined as the connection between the components that define the energy flow routes and control ports. Traditionally, HEVs were classified into two basic types: series and parallel. It is interesting to note that in 2000, some newly introduced HEVs could not be classified into these kinds.[4] Hence, HEVs are presently classified into four kinds—series hybrid, parallel hybrid, series–parallel hybrid, and complex hybrid—that are functionally shown in Figure 6.3.[5] Scientifically, the preceding classifications are not very clear and may cause confusion. In an HEV, there are two kinds of energy flowing in the drivetrain: mechanical energy and electrical energy. Adding two powers together or splitting one power into two at the power-merging point always occurs with the same power type, that is, electrical or mechanical, not electrical and mechanical. Perhaps a more accurate definition for HEV architecture may be to take the power coupling or decoupling features such as an electrical coupling drivetrain, a mechanical coupling drivetrain, and a mechanical–electrical coupling drivetrain.

Figure 6.3a functionally shows the architecture that is traditionally called a series hybrid drivetrain. The key feature of this configuration is that two electric powers are added together in the power converter, which functions as an electric power coupler to control the power flows from the batteries and generator to the electric motor, or in the reverse direction from the electric motor to the batteries. The fuel tank, the IC engine, and the generator constitute the primary energy supply, and the batteries function as the energy bumper.

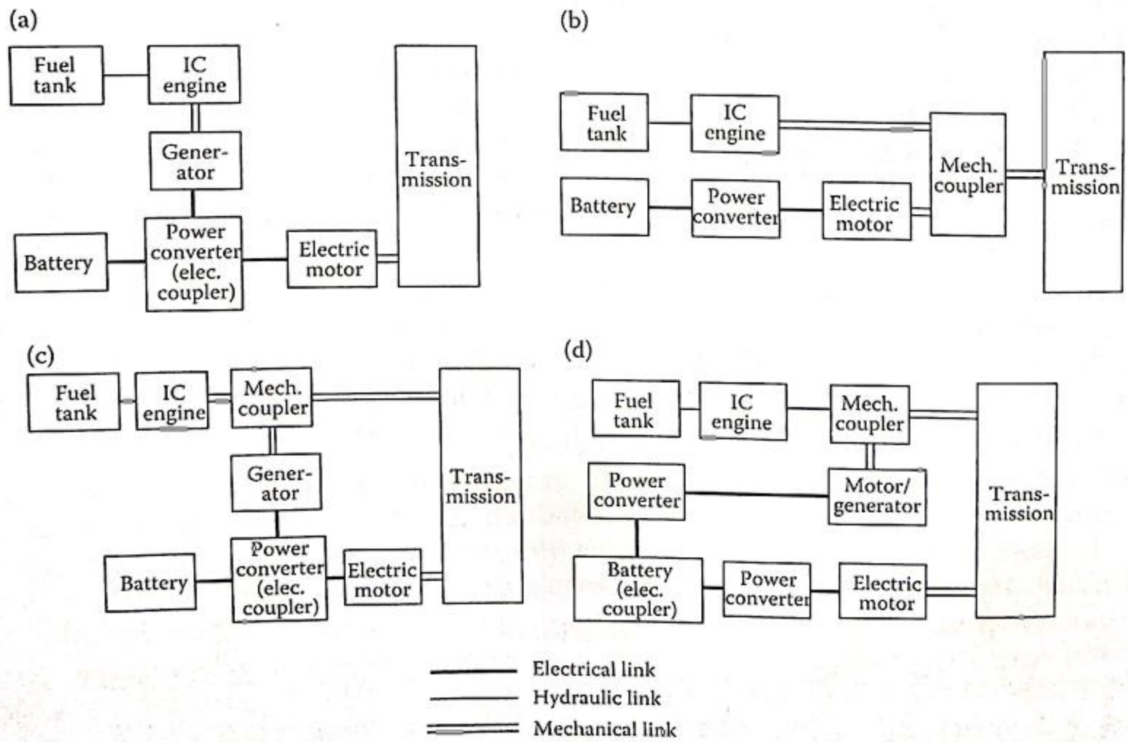


FIGURE 6.3
Classifications of HEVs. (a) Series (electrical coupling), (b) parallel (mechanical coupling), (c) series–parallel (mechanical and electrical coupling), and (d) complex (mechanical and electrical coupling).

Figure 6.3b shows the configuration that is traditionally called a parallel hybrid drivetrain. The key of this configuration is that two mechanical powers are added together in a mechanical coupler. The IC engine is the primary power plant, and the batteries and electric motor drive constitute the energy bumper. The power flows can be controlled only by the power plants—the engine and the electric motor.

Figure 6.3c shows the configuration that is traditionally called a series–parallel hybrid drivetrain. The distinguishing feature of this configuration is the employment of two power couplers—mechanical and electrical. This configuration is the combination of series and parallel structures, possessing the major features of both and more plentiful operation modes than those of the series or parallel structure alone. On the other hand, it is relatively more complicated and may be more expensive.

Figure 6.3d shows a configuration of the so-called complex hybrid, which has a similar structure to the series–parallel one. The only difference is that the electrical coupling function is moved from the power converter to the batteries, and one more power converter is added between the motor/generator and the batteries.

We will concentrate more on the first three configurations—series, parallel, and series–parallel.

Series hybrid Electric vehicle:

5.2.1 Series Hybrid Electric Drive Trains

A series hybrid drive train is a drive train where two power sources feed a single powerplant (electric motor) that propels the vehicle. The most commonly found series hybrid drive train is the series hybrid electric drive train shown in Figure 5.4. The unidirectional energy source is a fuel tank and the unidirectional energy converter is an engine coupled to an electric generator. The output of the electric generator is connected to an electric power bus through an electronic converter (rectifier). The bidirectional energy source is an electrochemical battery pack, connected to the bus by means of a power

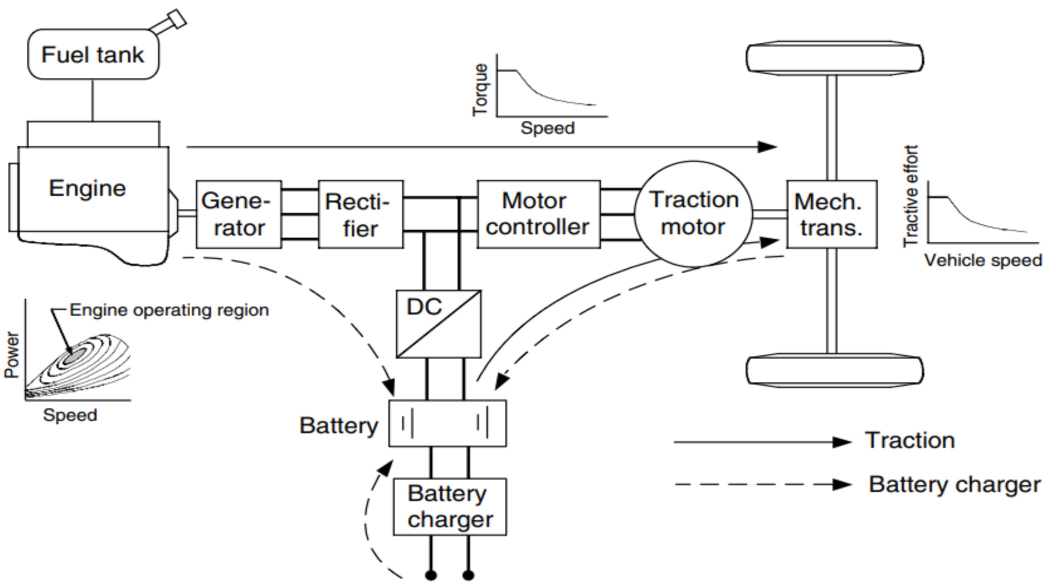


FIGURE 5.4
Configuration of a series hybrid electric drive train

electronics converter (DC/DC converter). The electric power bus is also connected to the controller of the electric traction motor. The traction motor can be controlled either as a motor or a generator, and in forward or reverse motion. This drive train may need a battery charger to charge the batteries by a wall plug-in from the power network.

Series hybrid electric drive trains potentially have the following operation modes:

1. Pure electric mode: The engine is turned off and the vehicle is propelled only by the batteries.
2. Pure engine mode: The vehicle traction power only comes from the engine-generator, while the batteries neither supply nor draw any power from the drive train. The electric machines serve as an electric transmission from the engine to the driven wheels.
3. Hybrid mode: The traction power is drawn from both the engine-generator and the batteries.
4. Engine traction and battery charging mode: The engine-generator supplies power to charge the batteries and to propel the vehicle.
5. Regenerative braking mode: The engine-generator is turned off and the traction motor is operated as a generator. The power generated is used to charge the batteries.
6. Battery charging mode: The traction motor receives no power and the engine-generator charges the batteries.
7. Hybrid battery charging mode: Both the engine-generator and the traction motor operate as generators to charge the batteries.

12.6.3 Series Hybrid Electric Vehicles

Series hybrid electric vehicles are powered by electric machines. As depicted in Figure 12.11c, series hybrid vehicles incorporate two electric machines and an IC engine in the propulsion system. One electric machine is directly attached with the IC engine and most of the time it functions as an electric generator (during starting of the IC engine, it acts as an electric motor). Another electric machine is integrated with the transmission system to deliver the propulsive power requirement of the vehicle. Since series hybrid electric vehicles incorporate a bigger electric machine in the propulsion system, their energy recovery capability is significantly higher than other types of HEVs. Series hybrid electric vehicles achieve six different operating modes as depicted in Figure 12.13. They can be described as

a. Electric machine is the only propulsive medium.
b. IC engine is supplying the propulsive torque/power demand.
c. IC engine and electric machines are supplying the propulsive torque/power demand.
d. Regenerative braking mode of the vehicle.
e. IC engine supplies the propulsive torque/power demand of the vehicle. The excess power of the IC engine is converted into electricity and stored in the battery system.
f. IC engine charges the battery system (also, battery can receive power from regenerative braking).

Since electric machines are capable of handling a wide range of speed–torque requirements of the vehicle, series hybrid electric vehicle architecture provides benefit for heavy-duty vehicles in

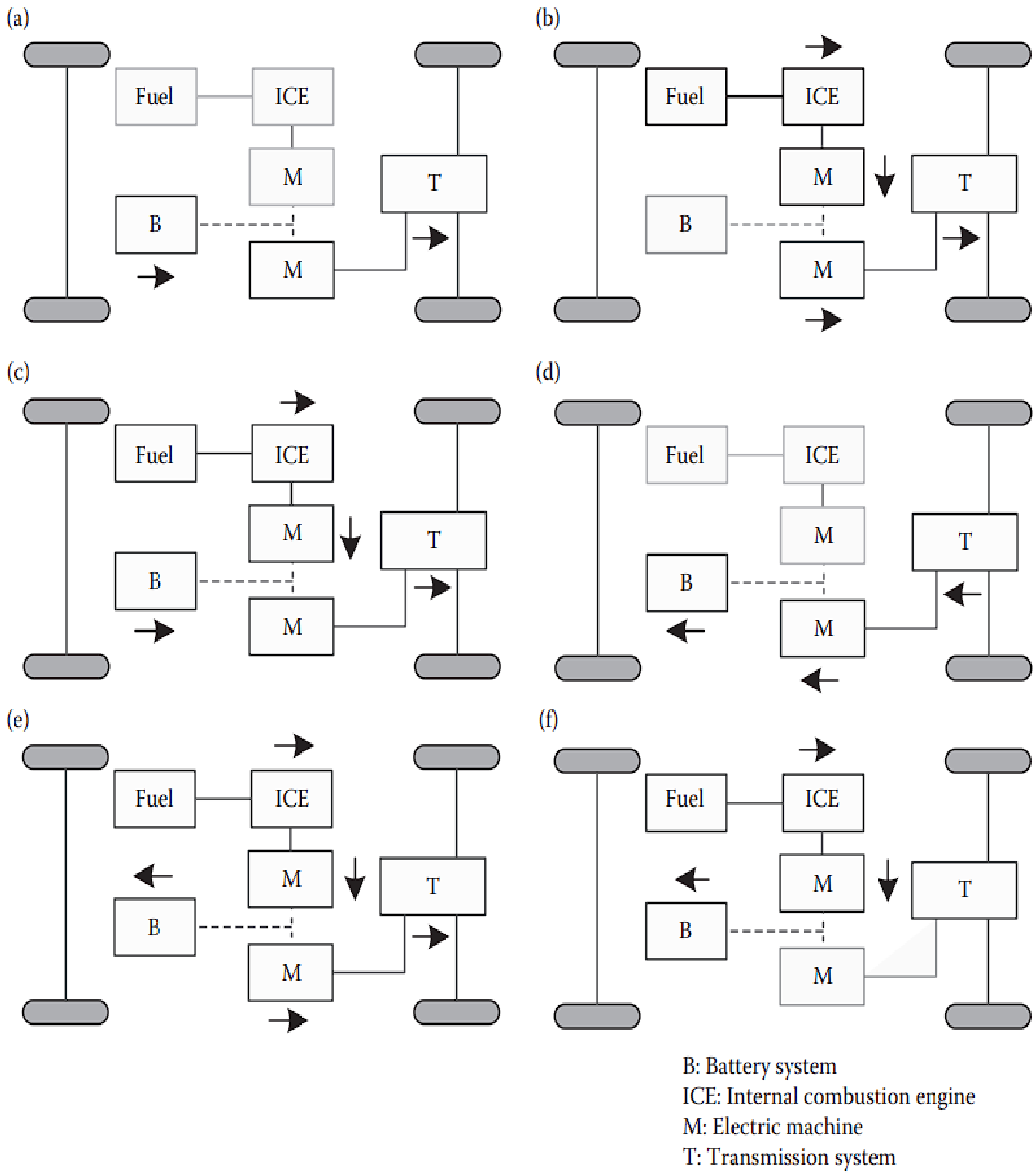


FIGURE 12.13 Operating modes of series hybrid electric vehicles: (a) Electric machine is the only propulsive medium; (b) IC engine is supplying the propulsive torque/power demand; (c) IC engine and electric machines are supplying the propulsive torque/power demand; (d) regenerative braking mode of the vehicle; (e) IC engine supplies the propulsive torque/power demand of the vehicle; (f) IC engine charges the battery system (also, battery can receive power from regenerative braking).

terms of simplifying the transmission system design. Since this architecture incorporates bigger propulsive components (e.g., to provide X kW power to the drive wheels, they incorporate 3X kW power sources), this architecture is not appropriate for light-duty vehicles. In heavy-duty vehicles, the space constraint is not very significant; however, space is limited in light-duty vehicles and it has to be effectively managed.

Series hybrid drive trains offer several advantages:

1. The engine is fully mechanical when decoupled from the driven wheels. Therefore, it can be operated at any point on its speed–torque characteristic map, and can potentially be operated solely within its maximum efficiency region as shown in Figure 5.4. The efficiency and emissions of the engine can be further improved by optimal design and control in this narrow region. A narrow region allows greater improvements than an optimization across the entire range. Furthermore, the mechanical decoupling of the engine from the driven wheels allows the use of a high-speed engine. This makes it difficult to power the wheels directly through a mechanical link, such as gas turbines or powerplants, with slow dynamics like the Stirling engine.
2. Because electric motors have near-ideal torque–speed characteristics, they do not need multigear transmissions as discussed in Chapter 3. Therefore, their construction is greatly simplified and the cost is reduced. Furthermore, instead of using one motor and a differential gear, two motors may be used, each powering a single wheel. This provides speed decoupling between the two wheels like a differential but also acts as a limited slip differential for traction control purposes. The ultimate refinement would use four motors, thus making the vehicle an all-wheel-drive without the expense and complexity of differentials and drive shafts running through the frame.
3. Simple control strategies may be used as a result of the mechanical decoupling provided by the electrical transmission.

However, series hybrid electric drive trains have some disadvantages:

1. The energy from the engine is converted twice (mechanical to electrical in the generator and electrical to mechanical in the traction motor). The inefficiencies of the generator and traction motor add up and the losses may be significant.
2. The generator adds additional weight and cost.
3. The traction motor must be sized to meet maximum requirements since it is the only powerplant propelling the vehicle.

<u>Parallel hybrid Electric vehicle:</u>

5.2.2 Parallel Hybrid Electric Drive Trains

A parallel hybrid drive train is a drive train in which the engine supplies its power mechanically to the wheels like in a conventional ICE-powered vehicle. It is assisted by an electric motor that is mechanically coupled to the transmission. The powers of the engine and electric motor are coupled together by mechanical coupling, as shown in Figure 5.5. The mechanical

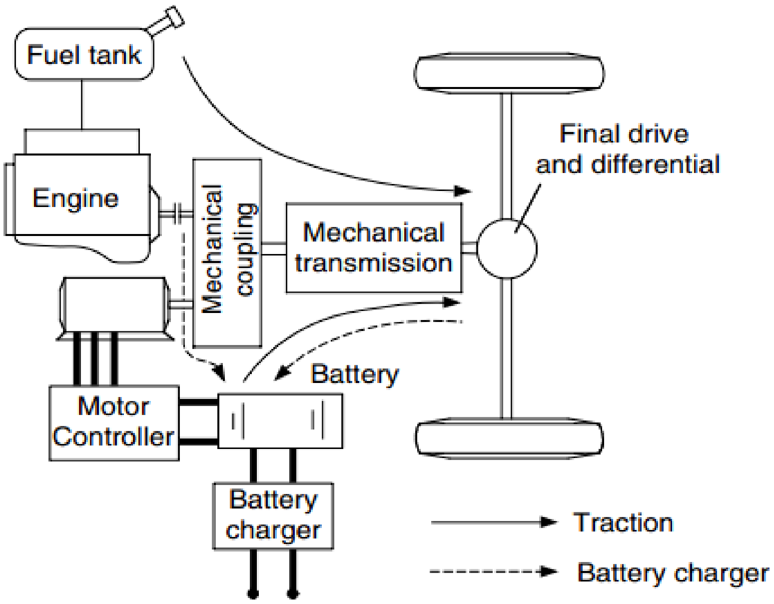


FIGURE 5.5
Configuration of a parallel hybrid electric drive train

combination of the engine and electric motor power leaves room for several different configurations, detailed hereafter.

12.6.2 Parallel Hybrid Electric Vehicles

Significant portion of the propulsive power in parallel hybrid electric vehicle is supplied by the electric machine. Typical electromechanical integration of the parallel hybrid electric vehicle is depicted in Figure 12.11b and it has two independent propulsive power flow paths such as electrical and mechanical paths. Therefore, depending upon the propulsive power requirement of the vehicle, electric only, mechanical only, or a combination of both can be chosen. Since parallel hybrid electric vehicles incorporate bigger electric machines, they have better regenerative braking capability compared to the mild hybrids, and therefore they show better fuel economy for city driving cycle and certain highway driving conditions. As depicted in Figure 12.12, there are four different operating modes that can be obtained in parallel hybrid electric vehicle.

a. IC engine supplies the propulsive torque/power demand.
b. Electric machine is the only propulsive medium.

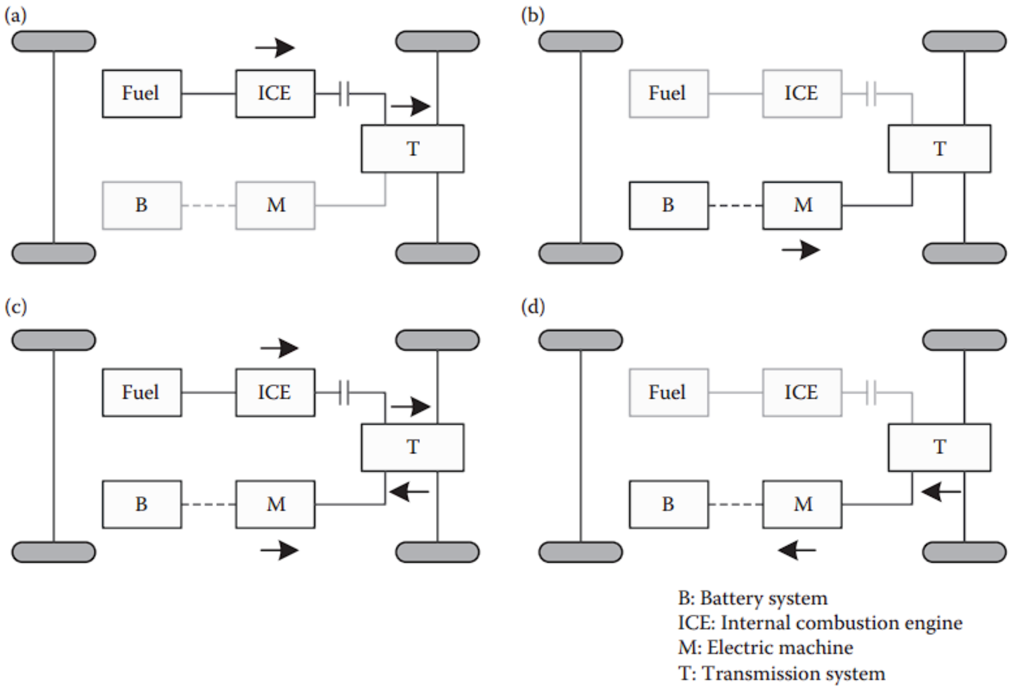


FIGURE 12.12 Operating modes of parallel hybrid electric vehicles: (a) IC engine supplies the propulsive torque/power demand; (b) electric machine is the only propulsive medium; (c) IC engine and electric machines supply the propulsive torque/power demand; (d) regenerative braking mode of the vehicle.

c. IC engine and electric machines supply the propulsive torque/power demand.
d. Regenerative braking mode of the vehicle.

<u>The advantages of the parallel hybrid drivetrain are:</u>

• both engine and electric motor directly supply torques to the driven wheels and no energy form conversion occurs, hence energy loss is less

• compactness due to no need of the generator and smaller traction motor.

<u>The drawbacks of parallel hybrid drivetrains are:</u>

• mechanical coupling between the engines and the driven wheels, thus the engine operating points cannot be fixed in a narrow speed region.

• The mechanical configuration and the control strategy are complex compared to series hybrid drivetrain. Due to its compact characteristics, small vehicles use parallel configuration. Most passenger cars employ this configuration.

Series and parallel HEV:

12.6.4 Series–Parallel Hybrid Electric Vehicles

The most popular hybrid electric vehicle in the market (Toyota Prius) is a series–parallel hybrid electric vehicle type, which incorporates two electric machines and an internal combustion engine for propulsion purposes, as shown in Figure 12.11d. Contrary to the series hybrid electric vehicles, series–parallel hybrid electric vehicles use low-power electric machines and both of them can act as motor and generator. Here, two electric machines and an IC engine are connected to the drive

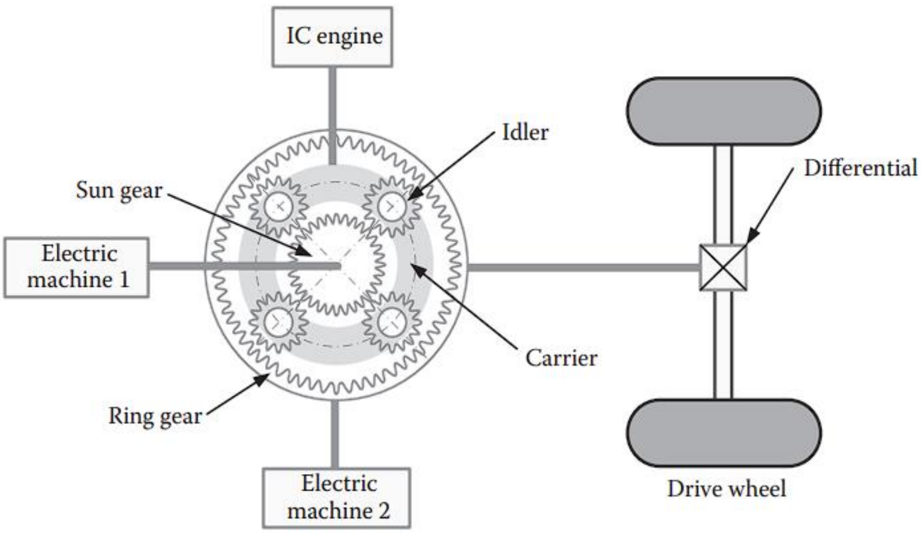


FIGURE 12.14 Planetary gear system and the connection diagram of propulsive systems in series–parallel hybrid electric vehicles. (Adapted from A. Emadi, M. Ehsani, and J. M. Miller, *Vehicular Electric Power Systems: Land, Sea, Air, and Space Vehicles*. New York: Marcel Dekker, December 2003.)

axle via a planetary gear system, as shown in Figure 12.14. The ingenious arrangement of this gear system allows the propulsive system to have much more flexibility while achieving different propulsive requirements. It also achieves many different power flow patterns by choosing different combinations of power sources. As depicted in Figure 12.15, series–parallel hybrid electric vehicles also achieve similar operating modes as series hybrid electric vehicles.

However, the control complexity of the vehicle increases as the number of power flow increases; therefore, many research works are focusing on how to effectively utilize different power sources to achieve various power flow patterns with higher energy efficiency.

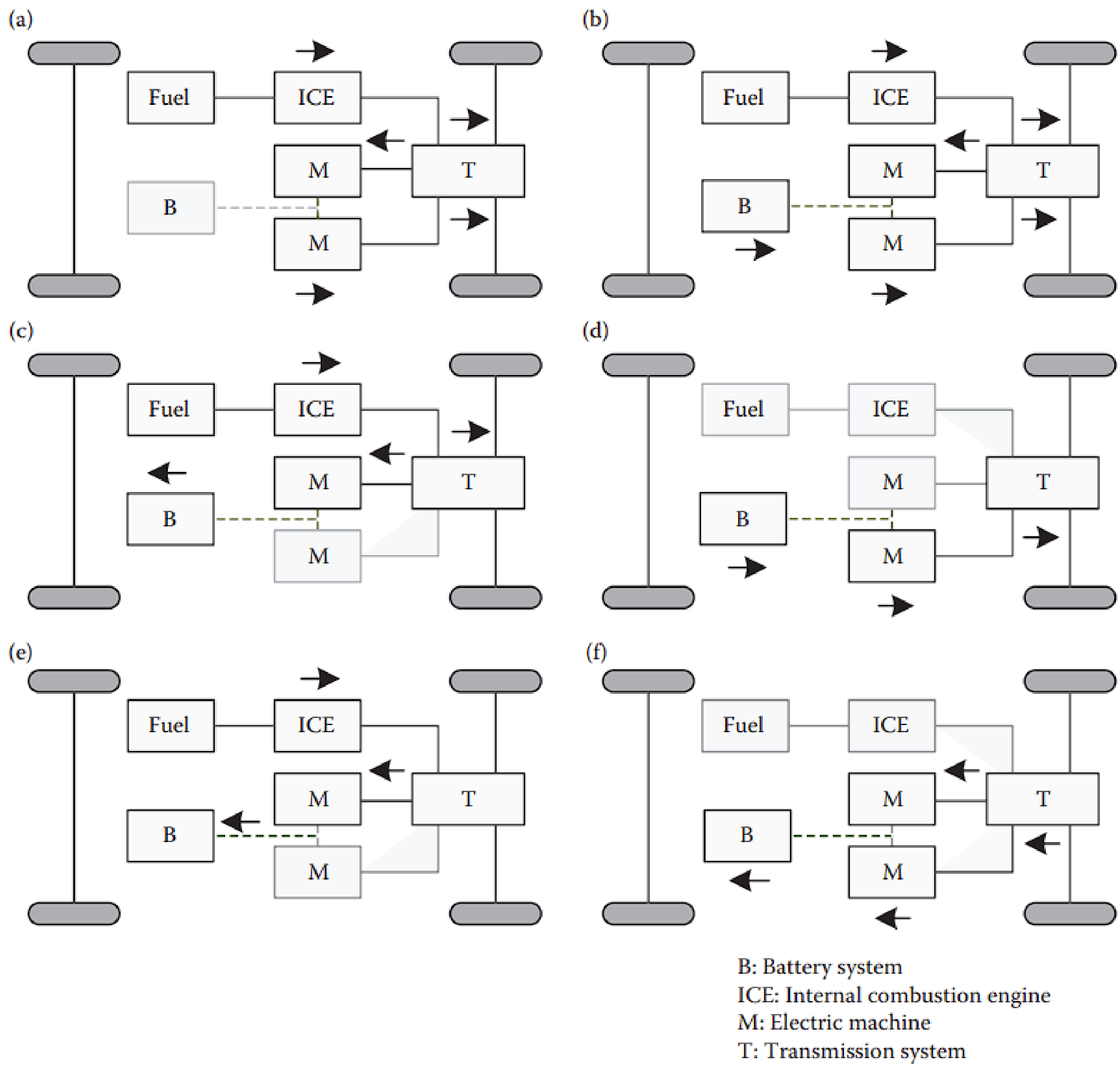


FIGURE 12.15 Operating modes of series–parallel hybrid electric vehicles: (a) IC engine is the only propulsive medium. Here part of the power produced by the IC engine is converter via motor generator to the traction wheels. (b) IC engine and electric batteries are supplying the propulsive torque/power demand. (c) IC engine is supplying the propulsive torque/power demand while the battery is charging. (d) Batteries are supplying the propulsive demand. (e) IC engine charges the battery while the vehicle is standstill. (f) Regenerative braking of the vehicle.

Complex HEV:

Power Flow Control Complex Hybrid Control

The complex hybrid vehicle configurations are of two types:

- Front hybrid rear electric
- Front electric and rearhybrid

Both the configurations have six modes of operation:

- **Mode 1:** During startup (**Figure 5a**), the required traction power is delivered by the EMs and the engine is in offmode.
- **Mode 2:** During full throttle acceleration (**Figure 5b**), both the ICE and the front wheel EM deliver the power to the front wheel and the second EM delivers power to the rearwheel.
- **Mode 3:** During normal driving (**Figure 5c**), the ICE delivers power to propel the front wheel and to drive the first EM as a generator to charge thebattery.
- **Mode 4:** During driving at light load (**Figure 5d**) first EM delivers the required traction power to the front wheel. The second EM and the ICE are in offsate.
- **Mode 5:** During braking or deceleration (**Figure 5e**), both the front and rear wheel EMs act as generators to simultaneously charge thebattery.

- **Mode 6:** A unique operating mode of complex hybrid system is **axial balancing**. In this mode (**Figure 5f**) if the front wheel slips, the front EM works as a generator to absorb the change of ICE power. Through the battery, this power difference is then used to drive the rear wheels to achieve the axle balancing.

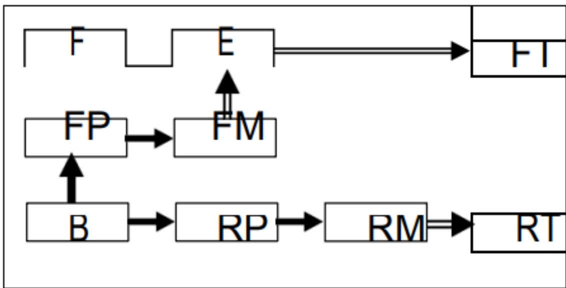


Figure 5a: Mode 1, startup

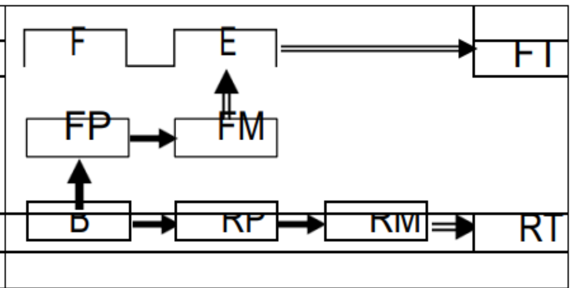


Figure 5b: Mode 2, full throttle acceleration

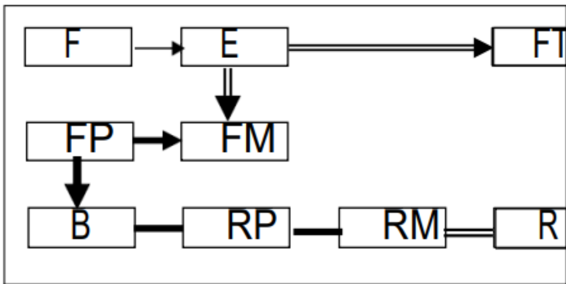


Figure 5c: Mode 3, vehicle propel and battery charging

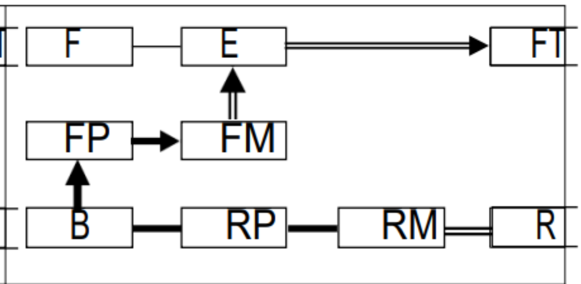


Figure 5d: Mode 4, light load

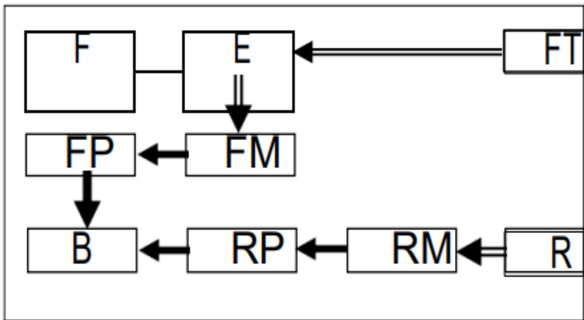


Figure 5e: Mode 5, braking or decelration

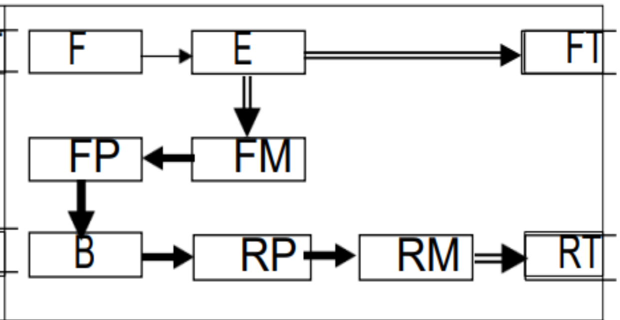


Figure 5f: Mode 1, axil balancing

B:Battery FM:Frontmotor FP: Front power converter FT: Frontaxel transmission E: ICE F: Fuel tank
RM:Rear motor RP: Rear power converter RT: Rear axle transmission[1]

Electricallink
Hydraulic link
Mechanicallink

In **Figures 6a-f** all the six modes of operation of front electric and rear hybrid is shown.

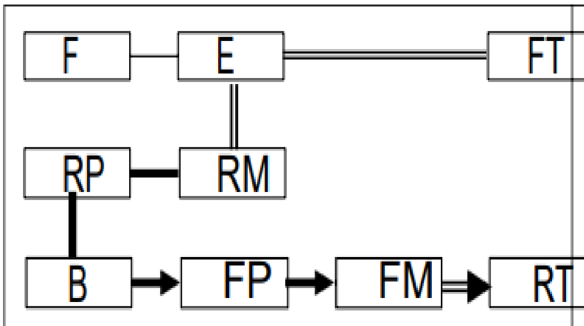


Figure 6a: Mode 1, startup

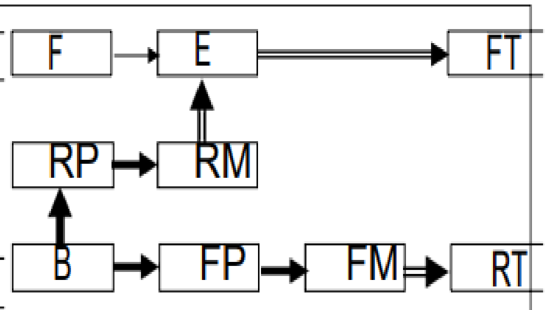


Figure 6b: Mode 2, full throttle acceleration

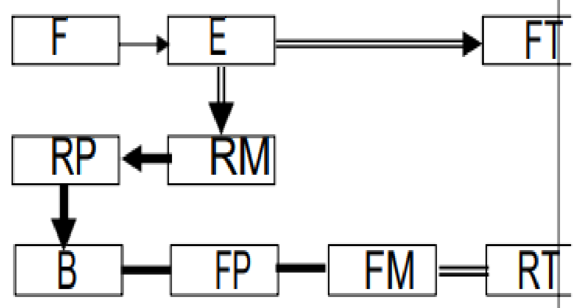


Figure 6c: Mode 3, vehicle propel and battery charging

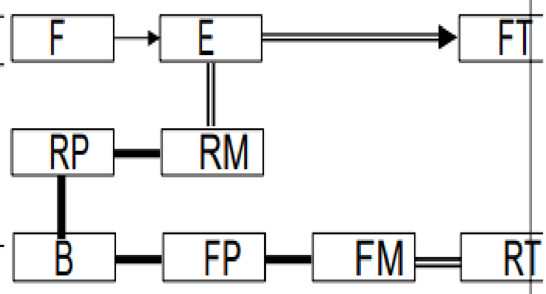


Figure 6d: Mode 4, light load

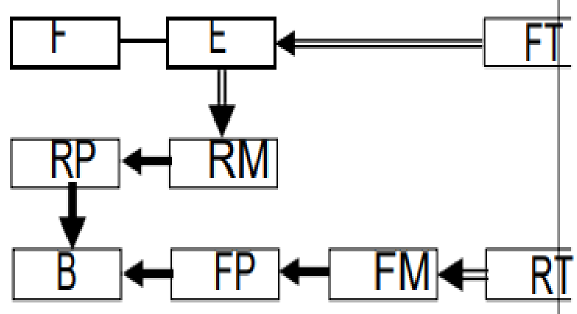


Figure 6e: Mode 5, brakingordecelration

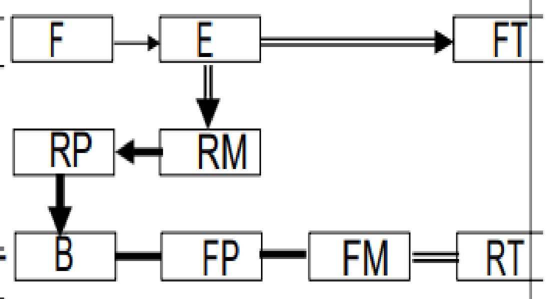


Figure 6f: Mode 1, axilbalancing

B:Battery RM:Rearmotor FP: Front power converter FT: Front axle transmission E: ICE F: Fueltank
RM:Rear motor RP: Rear power converter RT: Rear axle transmission[1]

Electricallink
Hydrauliclink
Mechanicallink

Plug-in hybrid vehicle(PHEV):

14.1 INTRODUCTION

Plug-in hybrid electric vehicle (PHEV) is another type of emerging vehicle that combines alternative fuels to displace the oil consumptions in conventional vehicles. As the name suggests, PHEVs are a special type of hybrid electric vehicles (HEVs). Similar to HEVs, PHEVs integrate the electric power path with the mechanical power path by using both conventional combustion engines (ICE) and electric machines. They can also be charged directly by plugging the wire into the wall to get power from the grid (hence the name).

The differences between PHEVs and HEVs primarily lie in battery capacity and recharging methods. PHEVs are equipped with larger battery capacities that are capable of operating on battery power alone for a considerable range, which is called all-electric driving range. Typically, this

all-electric range (AER) is designed to meet the daily driving requirements of PHEV owners, especially city drivers and suburban commuters. It is estimated that in Europe, 50% of trips are less than 10 km (6.25 miles) and 80% of trips are less than 25 km (15 miles). In the United Kingdom, 97% of trips are less than 80 km (50 miles). In the United States, about 60% of vehicles are driven less than 50 km (31.25 miles) daily, and about 85% are driven less than 100 km (60miles).[1] Therefore, a PHEV with an electric range of 60 miles would meet most of the trip range requirements in Europe and America, which is denoted as PHEV-60 (or PHEV-100 km). Figure 14.1 shows the typical U.S. daily travel distance distributions.[2]

TABLE 14.1

PHEVs, Different Types of HEVs, and Conventional Vehicle Comparisons

	Stop and Start	Regenerative Braking	Motor Assistance	Electric Driving	External Battery Charge
Conventional vehicles	Mostly no	No	No	No	No
Micro-HEVs	Yes	Minimum	No	No	No
Mild HEVs	Yes	Yes	Minimum	No	No
Full HEVs	Yes	Yes	Yes	Yes	No
PHEVs	Yes	Yes	Yes	Yes	Yes

In sum, PHEVs have many benefits:

1. *Petroleum consumption reduction:* The AER enables the switch from using conventional petroleum energy to electricity, which can be generated by various forms of resources. This significantly reduces the dependence on fossil fuel energy in the transportation sector, and provides a wide range of choices to charge the vehicles by generating electricity from renewable energies such as wind energy and solar energy. The benefit of the potential fuel reduction could be substantial. As a U.S. National Laboratory report found out, a 45% of fuel reduction can be achieved by replacing the conventional vehicle by a PHEV with 20 miles of electric travel range.[16]
2. *Emissions reduction:* As petroleum consumption is reduced, vehicle emissions due to the burning of the fossil fuels are remarkably reduced as a consequence. And, as discussed above, both the centralized generation of electricity and the use of renewable energy sources contribute to significant emission reductions. However, it should also be noted that since PHEVs typically work in the electric-only range that requires minimal engine operations, emissions might increase at the beginning of the engine start due to infrequent, multiple-engine cold starts. Methods and control algorithms[17] have existed to address such problems so that the overall emissions of PHEVs still remain much less than typical conventional vehicles under the same comparable size.
3. *Energy cost saving:* Besides the fuel consumption and emission reduction benefits, PHEVs also bring in the benefits of much lower energy costs. Although the exact cost saving depends on both long-term fossil fuel prices and electricity prices, it is estimated that, on an average, the fuel cost per mile of electricity is one-quarter to one-third of the cost per mile of fossil fuels for PHEV owners.[18] Meanwhile, governmental green energy incentives and certain privileges of lower auto-insurance compensate for the higher initial costs of PHEVs.
4. *Maintenance cost saving:* Since the mechanical components such as transmission and clutches are downsized and less frequently used, there are relatively fewer maintenance requirements regarding these parts, which are normally the maintenance concerns of conventional vehicles. Reducing the use of the engine also extends the engine life and reduces the frequency of oil changes. Besides, by taking advantage of regenerative braking, there is less friction wear on the mechanical brake, thus reducing the costs of frequently replacing the brake pad.
5. *Vehicle-to-grid (V2G) benefits:* PHEVs have the ability to supply the power back to the grid when they are connected to the grid; this serves to maintain a stable grid power level and to reduce power ripples. PHEVs could potentially serve as a temporary backup power source for home usage when grid power is not available.
6. *Customer benefits of home recharging:* PHEV owners enjoy the benefits of charging their vehicles in their garages or near their homes instead of looking for public-charging stations. This also allows the benefit of charging the vehicles at night when the vehicles are typically not in use and the electricity rate is the cheapest.

Constituents of PHEV:

14.3 COMPONENTS OF PHEVs

PHEV power trains are composed of the electric motor, generator, battery, and engine, which are all similar to those in HEV configurations. However, different sizes and power ratings are used in PHEVs.

14.3.1 Battery

Battery serves as the major energy source in PHEVs. Owing to the increased portion of the electric power system and the desired all-electric driving range, large quantities of batteries with sufficient energy capacity and power density are required in the PHEV power train to meet the demanded all-electric driving range. It is capable of supplying all the power required to propel the vehicle throughout the entire speed range, and it should be equipped with sufficient energy capacity to sustain the desired AER. Moreover, the battery also needs to provide all the power to the accessories such as air conditioning and power steering during the all-electric driving range. Thus, higher battery performance is demanded by PHEVs.

On the other hand, the overall vehicle weight and manufacturing costs are prone to the amount of the battery, which increases significantly as the battery packs increase. Moreover, large quantities of onboard vehicle batteries also bring in safety concerns about the fire hazards or high-voltage short circuits in either normal vehicle operations or accidents. Thus, battery technology plays the most critical role in developing PHEVs with regard to performance, costs, and reliability.

Different types of batteries are used in PHEVs. Lithium-ion batteries are currently the most widely used battery in PHEVs. They provide high-energy density and high-power density so that for the same weight of the battery, they enable longer all-electric driving range and better vehicle performance. They also have low self-discharge rate that may reduce the charging frequency and perform better under low usage rate.[19] On the other hand, safety is a big issue associated with lithium-ion batteries. To operate lithium-ion batteries in a continuous stable state, well-designed battery management system (BMS) and cooling systems are required. Specific conditions such as vibration, humidity, overcharge, short circuit, extreme weather, fire, and water immersion should all be taken into account during the design and manufacturing process. These add up the cost of lithium-ion batteries and how to bring down the cost is a hot topic in both academic research and industrial manufacturing. Despite the high price currently, lithium-ion batteries dominate the PHEV battery market due to their high performance. The top three best-selling PHEVs currently are: GM's Chevy Volt, Toyota's Prius Plug-in Hybrid, and Ford's C-Max Energi, and all these use lithium-ion battery technologies. Other variations of lithium-ion battery are also developed. For instance, BYD implemented lithium iron phosphate ($LiFePO_4$) batteries into F3DM PHEV and Qin PHEV.

Nickel–metal hydride (NiMH) batteries are another type of commercialized battery that has been implemented into PHEVs. It is capable of comparably high-power density and energy density. NiMH batteries operate in a much more stable state that is abuse tolerant compared with lithium-ion batteries. It also has a much longer life cycle than the lead-acid batteries. NiMH batteries are mostly used as the energy source for the first generation of HEVs developed before 2005 such as Toyota Prius and Ford Escape Hybrid because of their lower cost. However, they are gradually replaced by lithium-ion batteries as the technologies are getting better and the cost is coming down.

There are some other types of batteries that can also be used in PHEVs. Lead-acid batteries are the oldest rechargeable battery. The technology has been developed for more than 150 years and the cost is very inexpensive compared with other types of PHEV batteries. They have been widely applied as the low-voltage batteries in the automotive industry for starting, lighting, and ignition. Electric scooters, electric bicycles, wheelchairs, golf carts, and some microhybrid vehicles can also be equipped with lead-acid batteries. In addition, lithium-air batteries are also under research and development. They are capable of extremely high-energy density compared to the conventional gasoline fuels. Toyota is collaborating with BMW on the advanced battery development including lithium-air batteries. IBM is also developing the lithium-air batteries for automotive traction applications.

14.3.2 Electric Machine

Electric machine is another core component in PHEVs. They serve as the primary movers in PHEVs to output speed and torque to the output shafts that are connected with vehicle wheels. Regenerative braking is also achieved by running the electric machine in generating modes so that the kinetic energy is retrieved from the electric machine into batteries. Meanwhile, because the electric machine is the only power source to propel the vehicle in all-electric driving mode, a higher power rating is required for the electric machine so that it can meet the required speed and torque. For instance, GM's Chevy Volt is capable of 35 miles of all-electric driving range in which all the propulsion power and the accessory power come from the onboard electric machine that outputs the peak power of 111 kW and peak torque of 370 Nm.

It is common in PHEVs that a second electric machine is utilized to serve as a generator and engine starter. The secondary electric machine can also operate as in the motoring mode to assist with the vehicle performance such that both the electric machines operate in the motoring mode that maximum power and torque are generated. In the operations of none all-electric driving mode, the secondary generator helps to charge the battery so that the battery state of charge (SOC) remains above the threshold level and the vehicle can operate under hybrid electric mode, thus significantly increasing the driving range of PHEVs.

Compared with conventional gasoline engines, electric machines typically have much higher efficiency that is greater than 90% in most of the speed and torque range. The lifetime of onboard electric machines is also expected to be more than 15 years, which is competitive with conventional gasoline engines and there is no need for customs to replace the electric machines within the factory warranty time. Currently, interior permanent magnet machine is the most popular choice for traction drive applications due to its high efficiency, high torque density, and high-power density. The achieved power density of electric machines in vehicle propulsion applications is 1.2 kW/kg at the current stage.[20] Research is still going on to increase the power density of electric machines to further reduce the size and increase the power. The targeted power density of electric machines for traction drive in 2020 published by the U.S. Department of Energy is 1.6 kW/kg, requiring 33% increase on electric machine power density within the next 5–7 years.[20]

14.3.3 Engine

Similar to HEVs, PHEVs are also equipped with onboard internal combustion engines. The engines applied differ by the configurations of PHEVs. If the engine is connected in series with the electric machines, since the electric machines serve as the primary mover to supply the majority of power, the engine only functions to support the electric machines to share the peak load or charge the battery when the vehicles operate in the hybrid electric mode to extend the PHEV range. Thus, the size and power rating of the engine can be minimized and high engine efficiency is required at constant operating regions. On the other hand, if the engine outputs power in parallel with the electric machines, the engine is responsible for a substantial portion of power demanded from the power train. Thus, the engine should still retain its power and size accordingly, based on the power ratios in PHEVs between mechanical and electric power. In some PHEVs with large battery packs, the engine may only serve as a backup when the battery is depleted so as to extend the driving range and alleviate the range anxiety of customers.

Engines in PHEVs may also apply different technologies compared with engines in conventional vehicles. Atkinson cycle is used instead of the conventional Otto cycle in some of the PHEVs to further improve the vehicle efficiency. Atkinson cycle allows the engine intake, compression, power, and exhaust strokes that all happen in one revolution of a special designed crank shaft. A greater thermal efficiency is achieved at the expense of losing power density, which is acceptable in most of the PHEVs since the engine is not the major energy source and higher efficiency is preferred. Toyota Prius Plug-in Hybrid, Ford C-Max Energi, and Honda Accord Plug-in Hybrid all use Atkinson cycle for their engine propulsion. Toyota Prius Plug-in Hybrid, for instance, achieved 38.5% thermal efficiency by using Atkinson cycle in its 1.8-L gasoline engines.[21]

In addition, since the demand for engine power is downsized in PHEVs, systems associated with mechanical power system such as exhaust systems and mechanical transmissions can also be reduced to smaller scales.

14.3.4 Power Electronics

Power electronics in PHEVs include inverters, DC–DC converters, chargers, and BMS, which also typically come along with battery systems. Inverters serve to transform the DC power from the batteries into AC power to propel the electric machines. It is also necessary to retrieve the regenerative energy from the electric machines back into the battery pack by using the motor drive components.

Besides, an inverter and associated controller are typically needed for the onboard air conditioners that use AC machines.[22]

Multiple DC–DC converters are used to step up and step down the voltages at different levels to suit for various applications. A boost converter is used to increase the DC bus voltage up to a high level from the voltage of the battery pack, which is desired for the electric machines so that the constant torque region is extended and higher power and higher speed can be outputted at the rated operation point. This DC–DC converter should also be capable of bidirectional power transfer so that the power retrieved from the electric machines by regenerative braking can be transferred back into the battery. Multiple DC–DC converters are also needed to adjust the battery voltage to different low-voltage levels. For instance, a DC–DC converter is used to supply the power for the 12-V accessory loads and charge the 12-V low-voltage battery, while another DC–DC converter may be used to step down the battery voltage to a higher level to operate the high- power applications such as power-steering systems and compressing pumps.

AC–DC converters are needed in battery chargers to convert the AC power from the grid into DC power to charge the battery. Power factor correction and programmable digital controllers with proper voltage–current profiles are needed for high-energy battery packs.

Proprietary BMS are used to actively monitor the battery SOC and state of health (SOH). The power and state of each individual battery cell is also regulated and balanced by the BMS system. A good thermal performance is also ensured by properly adjusting the temperature on the battery cells, as well as controlling the flow rate of intake and outtake coolant.

Comparison of HEV and PHEV:

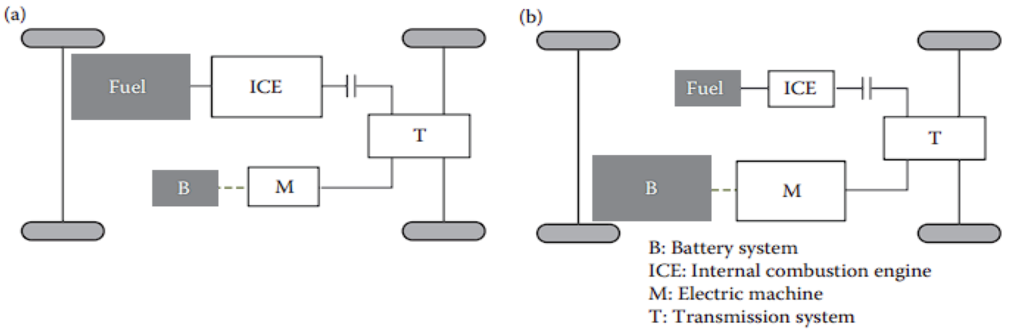


FIGURE 12.16 Difference between parallel and plug-in parallel hybrid electric vehicles: (a) parallel hybrid electric vehicle, (b) plug-in hybrid electric vehicle.

Extended range hybrid electric vehicles(EREVs):

15.4 RANGE-EXTENDED ELECTRIC VEHICLE

15.4.1 Range-Extended Electric Vehicle Introduction

Owing to the limited capacity and longer charging time of battery technologies, BEVs are inferior to conventional and hybrid vehicles in terms of achieving higher driving range. Therefore, BEVs are suitable for short driving objectives such as urban commutes, and so on. REEVs, however, increase the driving range of the vehicle by incorporating an auxiliary electrical power source to the propulsion system, as shown in Figure 15.16. As shown in Figure 15.17, the range extender can be a small internal combustion engine with a generator. Instead of powering the vehicle directly, the engine in a range extender is acting as an electricity generator to recharge the batteries. The battery capacity for a REEV is designed to satisfy a customer's average daily usage, while the range extender allows the vehicle to maintain an acceptable long drive range. Compared to the conventional ICEVs, fuel consumption and carbon dioxide emission for REEVs are significantly reduced.

15.4.2 Range Extenders

The engine-based range extender, as shown in Figure 15.18a, is commonly designed to be extremely compact, lightweight, and low-cost. The engine is controlled to operate in its economic zone with high efficiency. Other types of energy sources can also be used as the range extender. As shown in

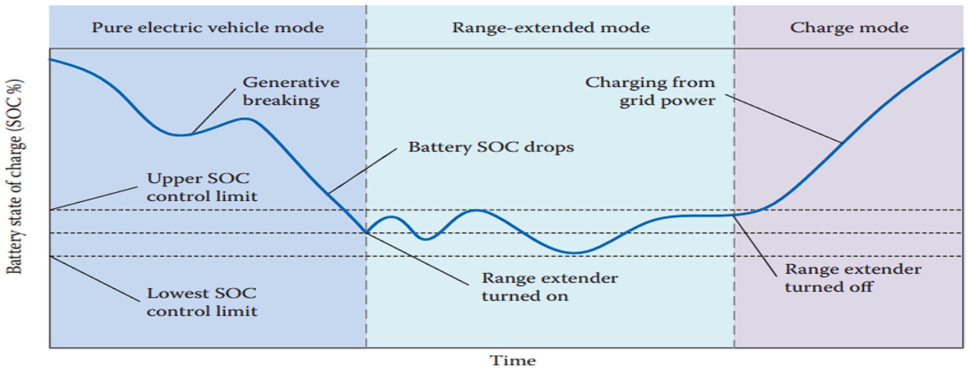


FIGURE 15.16 Range-extended electric vehicle operating modes.

Figure 15.18b, a fuel cell system can also be incorporated as a range extender to provide electric power to the powertrain system when the battery state of charge (SOC) reaches its power limit. Instead of carrying a bulky and heavy battery pack to achieve a long driving range, a fuel cell-based range extender can be used to downsize the battery pack and reduce the cost of the battery.

15.4.3 Range Extender Connection

Figure 15.19 shows two ways of connecting a range extender. In the first case, the range extended is connected to the battery, as shown in Figure 15.19a. The energy from the range extender flows in two directions: to the battery pack and to the load via a DC–DC boost converter and a DC–AC

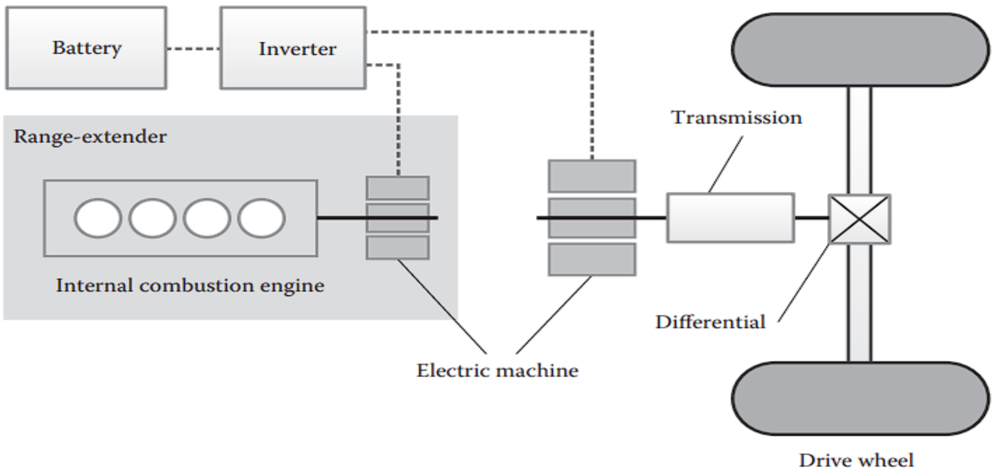


FIGURE 15.17 Powertrain configuration for a range-extended electric vehicle.

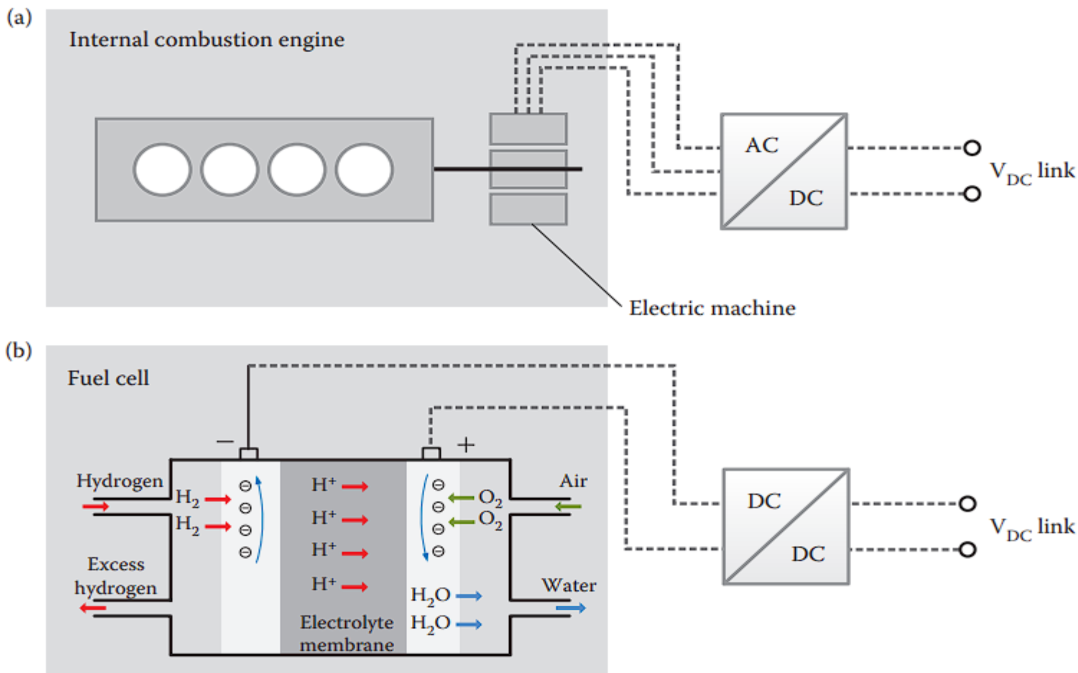


FIGURE 15.18 Two types of range extenders: (a) internal combustion engine-based range extender and (b) fuel cell-based range extender.

inverter. In this case, the total energy E_{load} flowing from the range extender to the load can be calculated by the following equation:

$$E_{\text{load}} = E_{RE}(\alpha \cdot \eta_{BAT} + \beta)\eta_{DC} \cdot \eta_{AC}, \tag{15.15}$$

where E_{RE} is the energy provided by the range extender, α is the percentage of the energy flowing from the range extender to the battery pack, β ($0 < \beta \leq 1$) is the percentage of the energy flowing from the range extender to the boost converter, η_{BAT} is the energy conversion efficiency for the battery pack, η_{DC} is the energy conversion efficiency for the boost converter, and η_{AC} is the energy conversion efficiency for the inverter.

The range extender can also be connected to the DC link, as shown in Figure 15.19b. In this case, the energy consumed by the load is given by

$$E_{\text{load}} = E_{RE}[\alpha \cdot (\eta_{DC})^2 \cdot \eta_{BAT} + \beta] \cdot \eta_{AC}. \tag{15.16}$$

Comparing the two equations above, it can be concluded that connecting the range extender to the DC link has a higher efficiency if the following holds true:

$$\beta > \alpha \cdot \eta_{DC} \cdot \eta_{BAT}. \tag{15.17}$$

If the total energy from the range extender flows to the load, the range extender should be connected to the DC link in order to increase the overall efficiency. It is preferable that the battery pack keeps its SOC during the extended range driving stage. The energy used to charge the battery pack from the range extender would finally move to the load in which process the energy conversion efficiency is reduced.

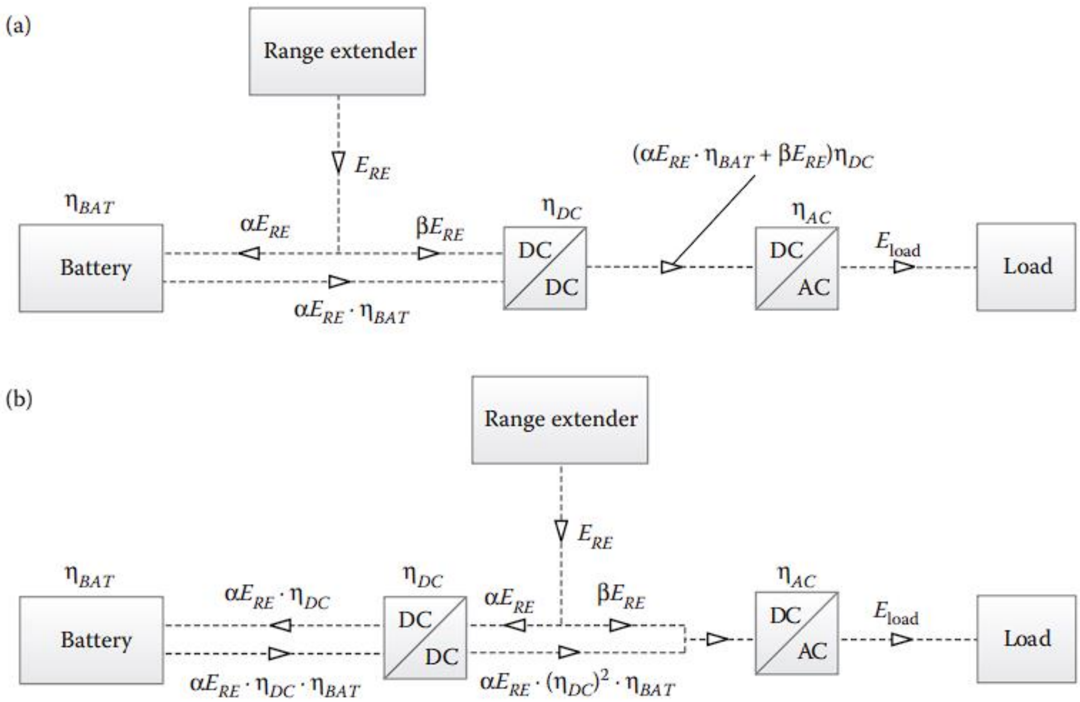


FIGURE 15.19 Types of range extender connections: (a) connected to the battery and (b) connected to the DC link.

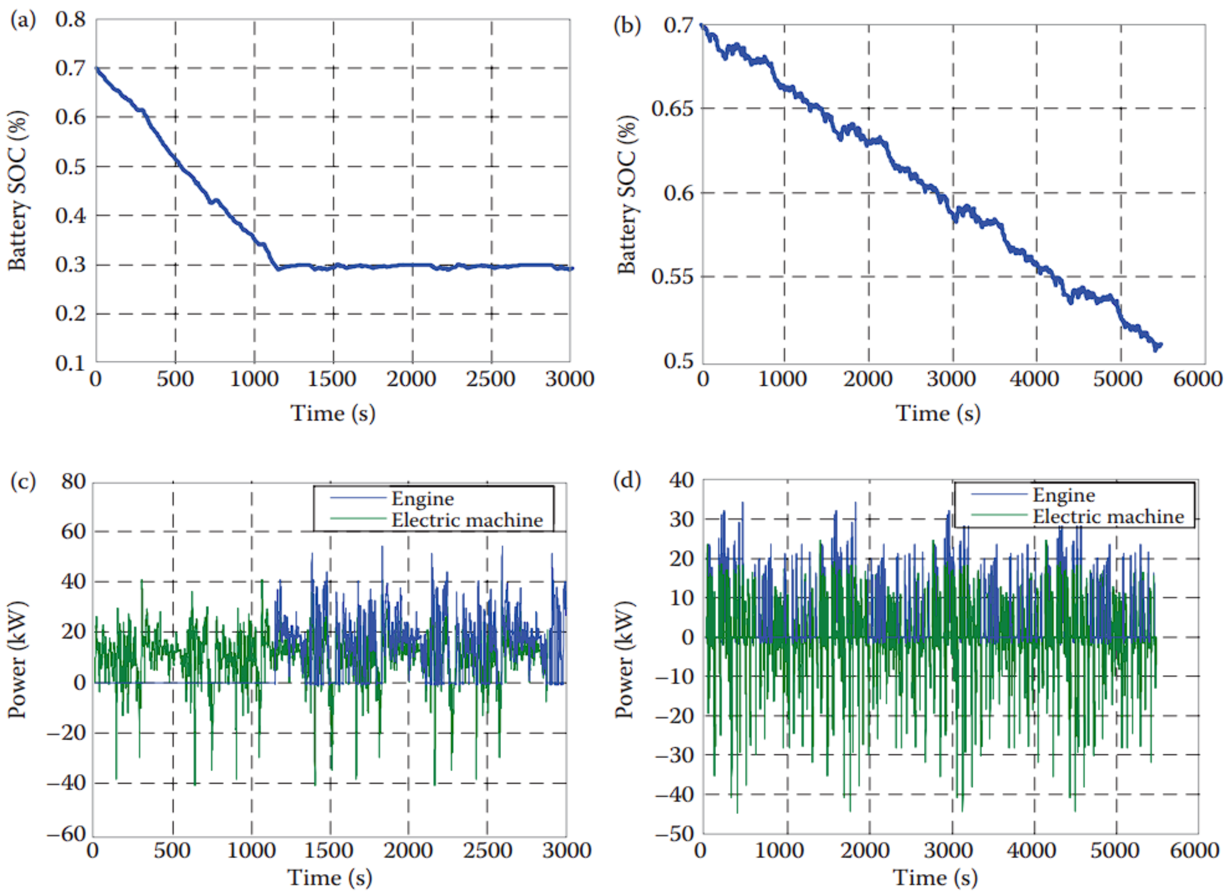
blended PHEVs:

14.6 CONTROL STRATEGY OF PHEV

PHEV operation modes can be either manually selected by the driver or automatically controlled based on the feedback signals of various vehicle systems such as the battery SOC, power demands, road loads, and expected trip length, among others. In terms of the control strategies, two methods are typically applied in PHEVs: the AER-focused and the blended control strategy.

The AER-focused control strategy takes the greatest advantage of the electric power and runs the vehicles intensively in AER mode before the battery SOC drops below a certain threshold level, after which, the engine starts and the system operates in CS mode. The AER-focused control strategy prioritizes fuel reduction and emissions reduction in short-range trips by running exclusively on battery power. It is more suitable for city drives and short-range suburban commuting where daily round-trip distance is normally within the electric range. Since all the power in AER mode comes from the electrical systems, batteries with large energy capacity and electrical machines and power electronics with high-power density are needed to satisfy all the drive performance requirements.

The blended control strategy utilizes both the engine and the electric machines to power the vehicle. On the basis of expected travel distance, the blended control strategy picked the most appropriate fuel/electricity combination so that the battery SOC decreases smoothly in a linear trend. It operates the vehicle under CD mode with the engine running in its high efficiency region all the time until the battery SOC drops below the preset threshold level, after which, the vehicle operates in CS mode, similar to the AER-focused control strategy. The blended control strategy prioritizes



the range extent. It achieves an extended range in CD mode by using either the engine dominant strategy or the electric dominant strategy. In the former strategy, the engine is operating in its optimal fuel regions and the electric machine is used to subsidize the additional power demands. The latter strategy mainly utilizes electric power; the engine turns on only when the road loads exceed the electric capacity.

Figure 14.16 illustrates the battery SOC based on AER-focused control strategy and the blended control strategy, respectively. Four of the UDDS driving cycles are applied for a typical series PHEV. Power from both the engine and the electric machine is presented under each control strategy as well.

The optimum control strategy thus should rely on the trip distance that one PHEV is going to travel. If the trip distance is well within the battery AER, AER-focused control strategy should be applied so as to achieve the maximum fuel displacement. When the trip distance is greater than the AER, the blended control strategy is preferred with the engine running in its high efficiency region throughout the trip to achieve the optimum fuel efficiency.

In addition, Figure 14.17 presents the difference in engine and electric machine operation points between UDDS (Urban Dynamometer Driving Schedule) cycle and HWFET (The Highway Fuel Economy Test) cycle, which simulate the vehicle-driving behaviors on local and highway, respectively. It can be observed that the electric machine operates frequently in the low-speed regions under the local driving scenario while it operates more frequently in the high-speed regions on the highway. It can also be observed that the electric machine operates frequently in the negative torque region under local driving so as to retrieve more regenerative braking energy. For both

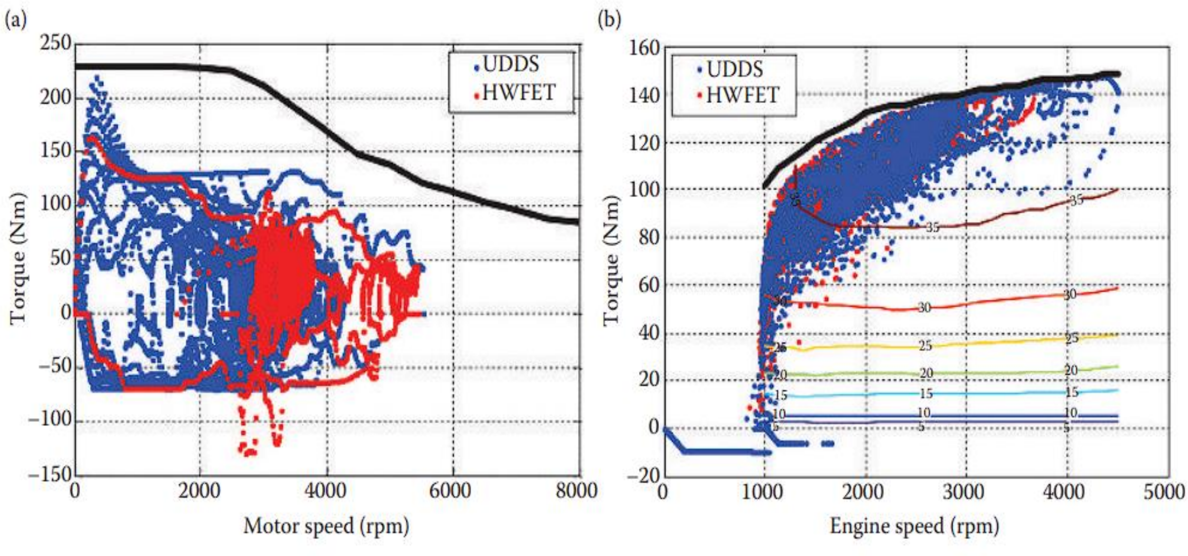


FIGURE 14.17 Operation points comparisons between drive cycles. (a) Motor operation point comparison, and (b) engine operation point comparison.

local and high way driving, the engine is largely controlled to be operated at high efficiency level. Different control strategies will result in different operation points for both the engine and the electric machine, thus affecting the fuel consumption as well as the emissions of the vehicle.

Fuel Cell vehicles and its constituents:

15.5.2 Fuel Cell Introduction

A fuel cell is an electrochemical energy conversion device, which combines hydrogen and oxygen to produce electricity and emits water as the by-product of this reaction. The proton exchange membrane fuel cell (PEMFC) and the alkaline fuel cell are two of the most commonly developed fuel cells for electric vehicle application.

Figure 15.20a shows the mechanism of a PEMFC. The electrolyte is an ~0.1-mm-thick proton-conducting plastic membrane, coated with a platinum catalyst. At the anode, hydrogen gives up its electron to the anode with the help of the catalyst. The electrolyte membrane is designed to allow only hydrogen ions to pass through. At the cathode, the hydrogen ions, oxygen, and electrons are bonded to form water. In this process, electrons flow from the anode to the cathode through the external load. As shown in Figure 15.20b, for alkaline fuel cells, alkaline electrolyte only allows

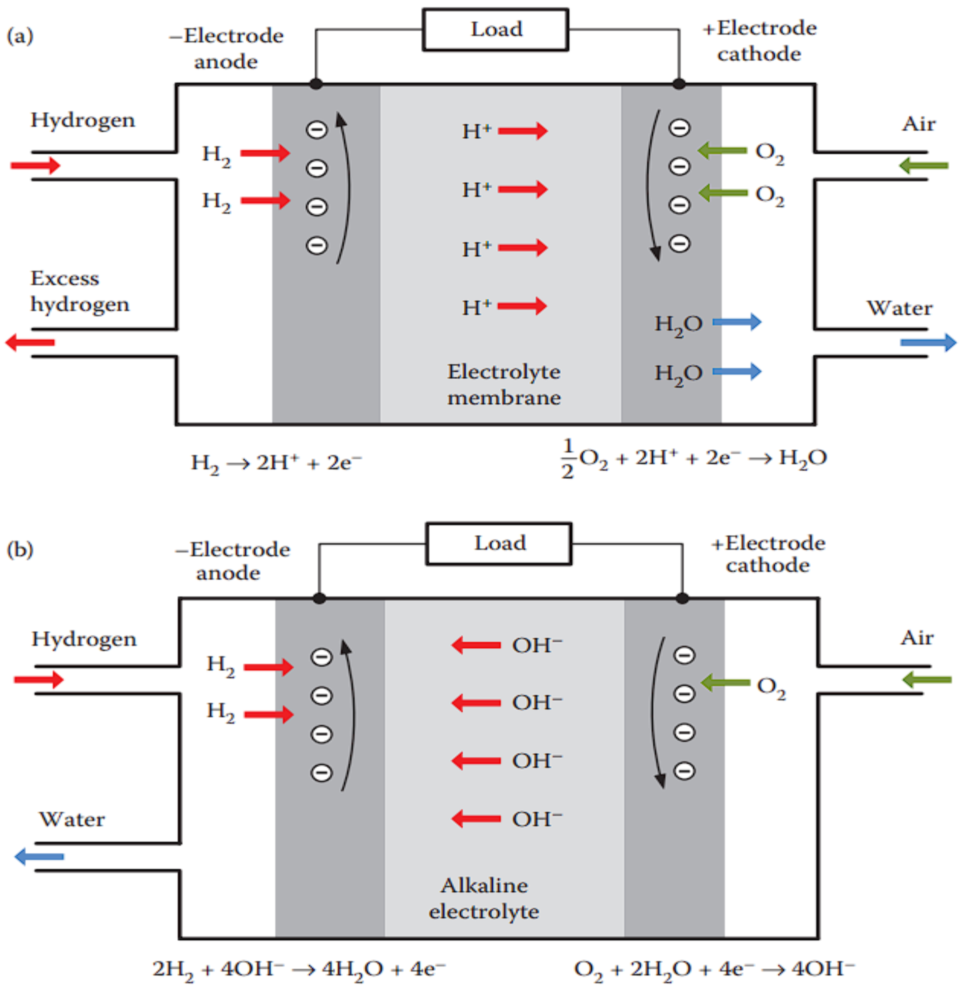


FIGURE 15.20 Schematic of fuel cells: (a) proton exchange membrane fuel cell and (b) alkaline fuel cell.

hydroxide to pass through. At the anode, hydrogen combined with hydroxide generates water and electrons; at the cathode, oxygen, water, and electrons are combined to create hydroxide.

4.1.2.1 Alkaline Fuel Cell (AFC)

In an alkaline fuel cell (AFC), an aqueous solution of potassium hydroxide (KOH) is used as the electrolyte. Compared to some other fuel cells where acidic electrolytes are used, the performance of the alkaline electrolyte is as good as the acid electrolytes, while being significantly less corrosive toward the electrodes. Alkaline fuel cells have been in actual use for a long time, delivering electrical efficiencies of up to 60%. They require pure hydrogen as fuel and operate at low temperatures (at 80°C); therefore, they are suitable for vehicle applications. Residual heat can be used for heating, but the cell temperature is not sufficiently high to generate steam that can be used for cogeneration.

4.1.2.2 Proton Exchange Membrane (PEM)

The proton exchange membrane (PEM) fuel cells use solid electrolytes and operate at low temperatures (around 80°C). Nafion is an example of solid polymer electrolyte. These fuel cells are also known as solid polymer membrane fuel cells. The electrical efficiency of PEM fuel cells is lower than that of the alkaline cells (about 40%). However, a rugged and simple construction makes these types of fuel cells suitable for vehicle applications. The PEM fuel cell and the AFC are currently being considered for vehicle applications. The advantage

of PEM cells is that they can tolerate impurity in the fuel, as compared to pure hydrogen which is needed in alkaline fuel cells.

4.1.2.3 Direct Methanol Fuel Cell (DMFC)

The direct methanol fuel cell (DMFC) is a result of research on using methanol as the fuel that can be carried on-board a vehicle and reformed to supply hydrogen to the fuel cell. A DMFC works on the same principle as the PEM, except that the temperature is increased to the range of 90 to 120°C such that internal reformation of methanol into hydrogen is possible. The electrical efficiency of DMFC is quite low at about 30%. This type of fuel cell is still in the design stages, because the search for a good electrocatalyst to reform the methanol efficiently and to reduce oxygen in the presence of methanol is ongoing.

4.1.2.4 Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cells (PAFC) are the oldest type with an origin that extends back to the creation of the fuel cell concept. The electrolyte used is phosphoric acid, and the cell operating temperature is about 200°C, which makes some cogeneration possible. The electrical efficiency of this cell is reasonable at about 40%. These types of fuel cells are considered too bulky for transportation applications, while higher efficiency designs exist for stationary applications.

4.1.2.5 Molten Carbonate Fuel Cell (MCFC)

Molten carbonate fuel cells, originally developed to operate directly from coal, operate at 600°C and require CO or CO_2 on the cathode side and hydrogen on the anode. The cells use carbonate as the electrolyte. The electrical efficiency of these fuel cells is high at about 50%, but the excess heat can be used for cogeneration for improved efficiency. The high temperatures required make these fuel cells not particularly suitable for vehicular applications, but they can be used for stationary power generation.

4.1.2.6 Solid Oxide Fuel Cell (SOFC, ITSOFC)

Solid oxide fuel cells (SOFCs) use a solid ionic conductor as the electrolyte rather than a solution or a polymer, which reduces corrosion problems. However, to achieve adequate ionic conductivity in such a ceramic, the system must operate at very high temperatures. The original designs, using yttria-stabilized

zirconia as the electrolyte, required temperatures as high as 1000°C to operate, but the search for materials capable of serving as the electrolyte at lower temperatures resulted in the "intermediate temperature solid oxide fuel cell" (ITSOFC). This fuel cell has high electrical efficiency of 50 to 60%, and residual heat can also be used for cogeneration. Although not a good choice for vehicle applications, it is at present the best option for stationary power generation.

The fuel cell features described above are summarized in Table 4.1. The usable energy and relative costs of various fuels used in fuel cells are listed in Table 4.2. The selection of fuel cells as the primary energy source in EVs and HEVs depends on a number of issues, ranging from fuel cell technology to infrastructure to support the system. Based on the discussion in this section, the choice of fuel cell for the vehicular application is an alkaline or proton exchange design, while for stationary applications, it will be the SOFC. The size, cost, efficiency, and start-up transient times of fuel cells are yet to be at an acceptable stage for EV and HEV applications. The complexity of the controller required for fuel cell operation is another aspect that needs further attention. Although its viability has been well-proven in the space program, as well as in prototype vehicles, its immature status makes it a longer-term enabling technology for an EV and HEV.

15.5.3 Fuel Cell Electric Vehicle Powertrain

Figure 15.21 shows a powertrain system for an FCEV. The primary components in the powertrain consist of a fuel tank, a fuel processor, a fuel cell as primary energy source, a battery pack, an electric machine as the traction motor, and so on. The vehicle controller takes command signals from the accelerator pedal and the brake pedal, the speed signal, the fuel cell power signal, and the battery signal, and sends the control signal to the fuel cell system. The power from the fuel cell and the battery pack combine to provide energy for the electric machine, which propels the vehicle through the transmission system.

Figure 15.22 shows that the fuel cell can be combined with other types of energy storage devices to provide power for the powertrain. Energy from the battery pack and the fuel cell can be combined to drive the electric motor, as shown in Figure 15.22a. The fuel cell in this configuration is more like a range extender. Figure 15.22b shows the parallel combination of the supercapacitor, and the

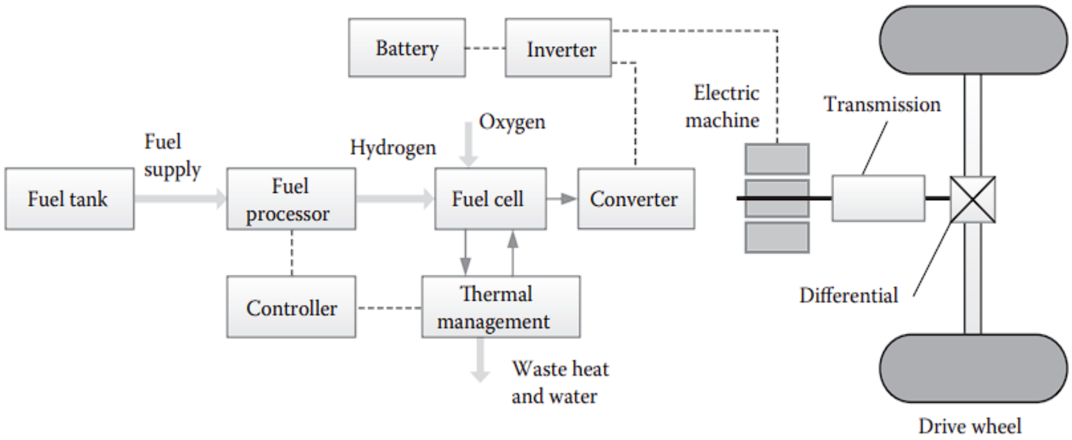


FIGURE 15.21 Powertrain system for a fuel cell electric vehicle.

fuel cell can work as the energy storage device for the electric vehicle. As stated earlier, the supercapacitor has high specific power and can assist the fuel cell in providing high power. In regenerative braking, peak power can be absorbed by the supercapacitor. Figure 15.22c and d shows two arrangements of the combination of the fuel cell and the flywheel. The mechanical energy stored in the flywheel can be converted into electrical energy first, and then combined with the energy from the fuel cell, as shown in Figure 15.22c. Figure 15.22d shows that the energy flowing out from the fuel cell can be converted into mechanical energy first and the energy from two energy devices then can be combined mechanically.

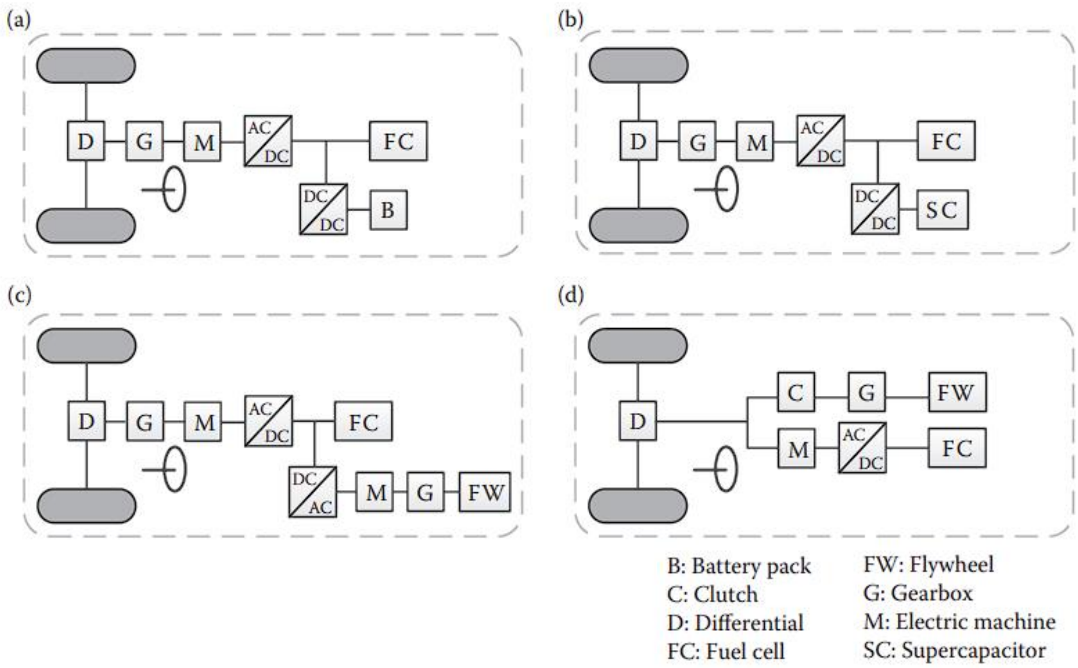


FIGURE 15.22 Fuel cells combined with other energy sources: (a) fuel cell combined with battery pack as energy source, (b) fuel cell combined with supercapacitor, (c) fuel cell combined with flywheel, and (d) another type of combination of fuel cell and flywheel, in which flywheel can provide mechanical energy directly and propel the vehicle through mechanical transmission.

TABLE 4.1 Fuel Cell Types

Fuel Cell Variety	Fuel	Electrolyte	Operating Temperature	Efficiency	Applications
Phosphoric acid	H_2, reformate (LNG, methanol)	Phosphoric acid	~200°C	40–50%	Stationary (>250 kW)
Alkaline	H_2	Potassium hydroxide solution	~80°C	40–50%	Mobile
Proton exchange membrane	H_2, reformate (LNG, methanol)	Polymer ion exchange film	~80°C	40–50%	EV and HEV, industrial up to ~80 kW
Direct methanol	Methanol, ethanol	Solid polymer	90–100°C	~30%	EV and HEVs, small portable devices (1 W to 70 kW)
Molten carbonate	H_2, CO (coal gas, LNG, methanol)	Carbonate	600–700°C	50–60%	Stationary (>250 kW)
Solid oxide	H_2, CO (coal gas, LNG, methanol)	Yttria-stabilized zirconia	~1000°C	50–65%	Stationary

Power management of plug in electric vehicles:

14.4 OPERATING PRINCIPLES OF PLUG-IN HYBRID VEHICLE

The operation modes of PHEVs largely depend on the battery SOC. Battery SOC is the term to describe the current state of the battery from 0% to 100%, with 0 standing for an empty battery and 100 meaning a full-charged battery. In comparison, HEVs typically remain battery SOC in a narrow range, for instance, 60%, to optimize the battery performance and ensure the required battery life. However, PHEVs typically demand greater depth of discharge (DOD) due to the higher dependence on the electricity energy source.

Because of the different operation patterns that PHEVs have from the HEVs, PHEV operations are more often classified by another set of specific operation modes[23]: charge-depleting (CD) mode, charge-sustaining (CS) mode, AER mode, and engine-maintenance mode. Figure 14.9 shows the

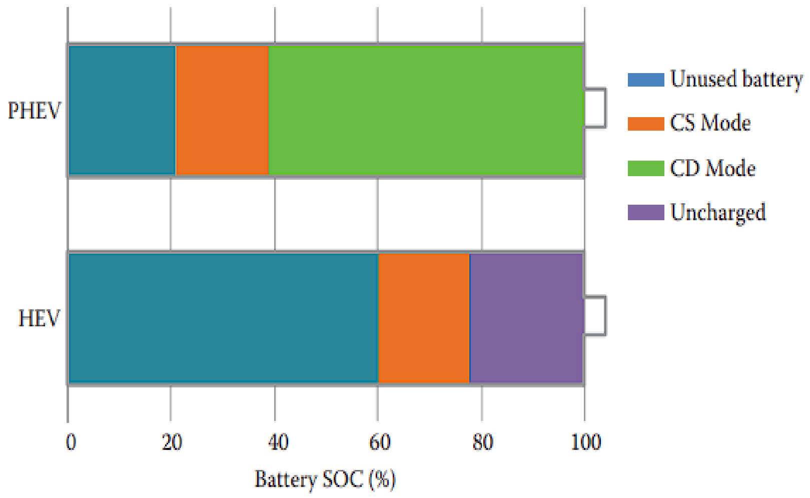


FIGURE 14.9 Battery performance comparison between HEVs and PHEVs. (From U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Plug-In Hybrid Electric Vehicle R&D Plan, Freedom Car and Vehicle Technologies Program, June 2007.)

14.4.1 Charge-Depleting Mode

CD mode refers to the PHEV operation mode in which the battery SOC on an average decreases while it may fluctuate along this trend. CD mode is frequently used at the first phase of PHEV operations, in which the SOC of the battery is sufficient to power the vehicle largely by electricity for a certain range. It prioritizes the use of electricity by drawing most of the power from the battery pack as long as the battery SOC stays above the preset threshold. However, if the demanded road power exceeds the battery power, the engine will also be running to assist the electric machine, thus enhancing the output tractive power.

CD mode is the primary operation mode in PHEV operations. In most city-driving and suburban-commuting cases, the round-trip distances are well within the PHEV battery power range. Thus, CD mode is largely utilized to take advantage of electric driving so that less fuel is used and fewer emissions are produced.

The extent of CD mode depends on the battery energy capacities and the frequencies of external battery charging. A larger battery pack with higher energy density would result in a longer CD mode range. However, this also contributes to much higher battery costs as well as vehicle weight increases. Recharging the PHEVs also helps to extend the CD range. With the installation of charging stations and the implementation of charging infrastructures at public places such as workplaces, parking lots, or in front of grocery stores, PHEVs can be readily recharged and CD ranges can be significantly increased in daily driving.

14.4.2 Charge-Sustaining Mode

CS mode refers to the PHEV operation mode in which the battery SOC on average maintains a certain level while it may frequently fluctuate above or below this level. CS mode utilizes both the engine and the electric machine to supply the vehicle power while keeping the SOC of the battery pack at a constant level. It is equivalent to the HEV operation mode in which the engine is mostly running within its optimal fuel efficiency range and the electric machines supply the power ripples. Engine power assistance and hybrid battery charging are realized in the CS mode to extend the driving range.

In PHEV operations, CS mode is more often used after the CD range when the battery power is discharged to a certain low threshold. Once the battery power is insufficient to power the vehicle on its own, the engine starts to supply the vehicle with petroleum combustion power. Both the engine and the electric machine operate together, coordinated under HEV operation mode. This takes advantage of the HEV operation benefits; so, high fuel efficiency is gained while the battery SOC is maintained at a certain level. Thus, the CS mode operation significantly increases the PHEV driving range compared with the CD mode without further increasing battery costs.

The combination of CD and CS mode enables energy use from two energy sources. The electricity works as the primary energy carrier to drive the vehicles in the preferred CD mode. The batteries can be recharged from external electric energy sources by plugging the vehicles into external power outlets. They can also be recharged by operating the vehicle in the CS mode, in which the engine utilizes the secondary energy carrier, the petroleum fuel, to generate power. In PHEVs, both energy sources are carried onboard the vehicles as they are stored in battery packs and fuel tanks. However, electricity is much preferred because it can be generated by a wide variety of cheaper energy sources, including coal, nuclear, natural gas, wind, hydro, and solar energy, and it greatly reduces vehicle tailpipe emissions. Thus, large packs of battery are normally required on PHEVs while relatively small fuel tanks are used.

14.4.3 AER Mode

As the name suggests, the AER mode uses electricity exclusively as its energy source to power the vehicles. The engine is shutoff during the AER mode while the electric machine supplies all the power by drawing energies from the battery pack. AER mode is similar to CD mode to a large extent, except that AER mode does not use the engine to assist the power output. The maximal range per charge depends on the onboard battery capacities. AER mode is often activated by manually switching under the command of the vehicle driver either to gain more fuel economy or to obey the rules in certain electric-only driving zones.

14.4.4 Engine-Maintenance Mode

Unlike the other operation modes, the engine-maintenance mode is not designed to propel the vehicle in PHEVs. Instead, it mainly functions to maintain the engine and prevent the fuel from being stale. This is useful for situations in which the driving range is always less than the AER and the vehicle gets recharged frequently. Thus, only AER mode is used and the engine never starts, which may cause problems for both engine components and fuel after a long time of nonuse.

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As the name suggests, the AER mode uses electricity exclusively as its energy source to power the vehicles. The engine is shutoff during the AER mode while the electric machine supplies all the power by drawing energies from the battery pack. AER mode is similar to CD mode to a large extent, except that AER mode does not use the engine to assist the power output. The maximal range per charge depends on the onboard battery capacities. AER mode is often activated by manually switching under the command of the vehicle driver either to gain more fuel economy or to obey the rules in certain electric-only driving zones.

14.4.4 Engine-Maintenance Mode

Unlike the other operation modes, the engine-maintenance mode is not designed to propel the vehicle in PHEVs. Instead, it mainly functions to maintain the engine and prevent the fuel from being stale. This is useful for situations in which the driving range is always less than the AER and the vehicle gets recharged frequently. Thus, only AER mode is used and the engine never starts, which may cause problems for both engine components and fuel after a long time of nonuse.